Study of the combined effect of adding silica fume and red brick waste on the physico-mechanical properties of cement composites reinforced with treated Doum (Chamaeropshumilis) plant fibers

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ABSTRACT

The objective of this study is to examine the effect of using mineral additives from recyclable sources, such as silica fume and red brick waste, as partial substitutions for cement on the physico-mechanical properties of cement composites reinforced with plant fibers from the xerophytic Doum plant (Chamaeropshumilis). The aim is to develop bio-sourced, sustainable, and economically advantageous construction materials for potential applications in the construction and civil engineering industry.

The results have shown that the incorporation of these mineral additives led to an increase in the bulk density of the composites. The highest bulk density was achieved with an optimal ratio of 10% silica fume and 5% red brick waste by weight of cement, resulting in a 28% increase compared to the fibered control mortar. Additionally, these composites exhibited a reduction in water absorption, with a decrease of up to 47.5% compared to the fibered mortars without additives.

The values of ultrasonic pulse velocity (UPV) also increased with the incorporation of additives, indicating improved quality of the composites. Regarding compressive strength, a significant improvement was observed, with an optimal increase of 109% at 90 days for mixtures containing 10% silica fume and 5% red brick waste. However, a higher substitution rate resulted in a decrease in strength.

The composites also showed an increase in flexural strength, with improvements of up to 26% compared to the fibered control mortar. The best results were obtained with 10% silica fume and varying rates of red brick waste.

In conclusion, the incorporation of silica fume and red brick waste in cement-based composites led to improvements in properties such as bulk density, water absorption, ultrasonic pulse velocity, and mechanical strength, with optimal additive ratios.

KEYWORDS : Substitution,recycling,composites, Silica fume,red brick waste, Cement, Doum fibers.

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1. Introduction

Currently, the world is facing a real energy crisis characterized by an energy shortage caused by various factors, including the rapid economic recovery after the Covid-19 pandemic and the invasion of Ukraine by Russia in February 2022. As a result, reducing energy consumption has become a major concern for many countries. The construction sector represents the largest global energy consumer, accounting for approximately 36% of global energy consumption. When considering the energy expended for construction and demolition, the energy share even amounts to 50% of total energy consumption [1]. Furthermore, this sector also contributes to 40% of annual global greenhouse gas emissions [2].

In many developed countries, considerable efforts have been made to address the economic issues in the construction sector. Energy challenges, increasing raw material costs, and the continuous depletion of natural resources have led to studies exploring the possibility of valorizing plant resources and recycling industrial or construction and demolition waste as construction materials in the building and public works sector.

The use of natural fibers, particularly plant fibers, is expanding in the field of composite materials, offering an interesting alternative in the construction sector. Plant fibers have several advantages: they are biodegradable, locally available at low cost, lightweight, have good mechanical properties, are renewable, CO2-neutral, and require low energy for production [3–6].

However, natural fibers also have several disadvantages. Vegetable fibers have limited durability in alkaline matrices due to the degradation of non-cellulosic components such as hemicellulose and lignin [7]. Additionally, the high water absorption and storage capacity, as well as fiber swelling, result in dimensional variations and microcracks around the fiber-matrix interface zone, negatively affecting the interfacial bond and mechanical performance of composite materials [7–9].

Therefore, there is a growing interest in improving the durability of plant fiber-reinforced cement composites and enhancing the interfacial adhesion between fibers and the matrix. This can be achieved through surface modification of fibers using chemical treatments, which have

been the subject of numerous studies, or by modifying the matrix using pozzolanic products to reduce its aggressiveness towards fibers.

In this context, it would be advantageous to reuse, recycle, and valorize building and industrial waste such as red brick waste and silica fume in the housing sector. This would improve the performance and durability of composite materials, reduce construction costs, preserve natural resources, and decrease energy consumption and greenhouse gas emissions.

Therefore, the objective of this study is to investigate the influence of using mineral additives from recyclable sources (silica fume and red brick waste) on improving the physico-mechanical performance of plant fiber-reinforced cement composites derived from the xerophytic plant Doum (Chamaeropshumilis), in order to obtain sustainable, high-performance, and cost-effective bio-based construction materials.

2. Characterization of used materials

2.1. Doum plants and fibers

The Chamaeropshumilis, also known as the dwarf palm, Doum palm, or Doum, is a small palm tree that is part of the flora of the Mediterranean basin (Figure 1). It grows in dry areas, on rocky or sandy terrain, forming a recognizable dwarf clump with its green fan-shaped leaves. Traditionally, Doum leaves are used in the production of coarse ropes, mats, hats, canvas, mats, and baskets [7,10]. Doum fibers have a significant water absorption capacity, with a saturation water absorption coefficient of 171%. Additionally, these fibers have a low bulk density of 447 kg/m^3 and significant mechanical properties, with a tensile strength of approximately 140 MPa and an elastic modulus of 6GPa [7]. In this study, Doum fibers were treated with a 1% NaOH solution for 30 minutes at room temperature, following the method developed by Achour et al. [7].

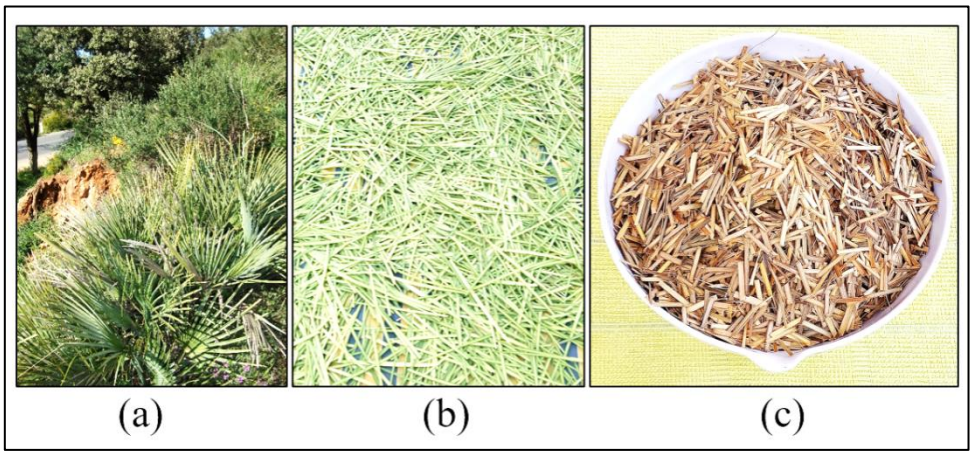

Figure 1. (a) Doum plant, (b) Doum leaves et (c) Treated Doum fibers.

2.2. Cement

The cement used in this experiment is a compound Portland cement C.P.J CEMII/B 42.5 N, known as MATINE according to the Algerian standard NA442. It is supplied by the LAFARGE cement plant located in HammamDalaa, M'sila.

The characteristics of the cement [11] are as follows:

- Specific surface area (Blaine): 4200 cm^2/g
- Density: 3.13 g/cm^3

The mineral and chemical composition of the cement [11–13] is presented in the following Table 1:

Table 1. Chemical and mineralogical compositions of cements.

Chemical composition (%)		Mineralogical compositions (%)	
SiO_2	18.8	C_3S	60 ± 3.0
Al_2O_3	4.2	C_2S	15 ± 3.0
Fe_2O_3	2.1	C_3A	7.5 ± 1.0
CaO	61.6	C_4AF	11 ± 1.0
MgO	2.1		
SO_3	2.9		
Na_2O	0.10		
K_2O	0.75		
Free CaO	6.5		
Loss on ignition	0.65		

2.3. Sand

In this experiment, a crushed limestone sand with a particle size of 0/4 is used. This sand is locally available and sourced from a quarry in the Tipaza province region.

The characteristics of the crushed limestone sand are as follows:

- Particle size: 0/4 (the sand passes through a 4 mm sieve)

- Apparent density: 1.51 g/cm^3.

2.4. Water used

In this study, tap water produced and distributed by the Algerian Water and Sanitation Company (SEAAL) in Tipazawas used for the mixtures. This tap water complies with Algerian quality and potability standards established by the competent authorities.

2.5. Silica fume

Silica fume is an industrial waste generated during the production of silicon and ferrosilicon. In this study, the silica fume used, named "MEDAPLAST HP," is supplied by the Algerian company "GranitexAlgérie" (Figure 2). This company specializes in the production of admixtures, mortars, and resins, in accordance with the NFP 18-502 standard [14]. Silica fume is a microsilica-based additive that appears as a fine gray powder. It has a silica content of approximately 95% and possesses high fineness. Additionally, it exhibits pozzolanic properties, which enhance the density, interfacial adhesion, mechanical properties, and durability of cement composites. In this study, silica fume was used as a partial substitute for cement. Its physical characterization and chemical composition are presented in Table 2.

Figure 2. Silica fume used in this study.

Table 2. The physical properties and chemical composition of silica fume.

Chemical composition (%)		Physical characteristics	
SiO_2	95	Bulk density	0.65
Al_2O_3	1.00	True density	2.24
Fe_2O_3	1.00	Specific surface area	23000 m^2/kg

CaO	1.50
MgO	1.00
SO_3	0.10
Na_2O	0.6
SiC	1.50

2.6. Red brick waste

In this study, the red brick waste was collected from a local brick kiln. These are fragments of fired clay bricks that have been calcined at a temperature of approximately 1000°C. These fragments were considered waste by the manufacturing plant, resulting in a significant amount of disposal. To prepare the material, the red brick waste was washed and dried. Subsequently, the dry samples were ground using an agate mortar and a grinder until a powder passed through an 80 µm sieve (Figure 3). This red brick waste powder is primarily composed of silica, an important mineral in pozzolanic reactions. During cement hydration, silica reacts with lime, promoting the formation of hydrated calcium silicates [15]. This leads to the improvement of the mechanical characteristics of cement-based composite materials. It is worth noting that the reuse of red brick waste in composite materials offers an environmental advantage by reducing waste and harnessing the pozzolanic properties of the silica present in these waste materials. The chemical and physical properties of the red brick waste powder [16, 17] are presented in Table 3.

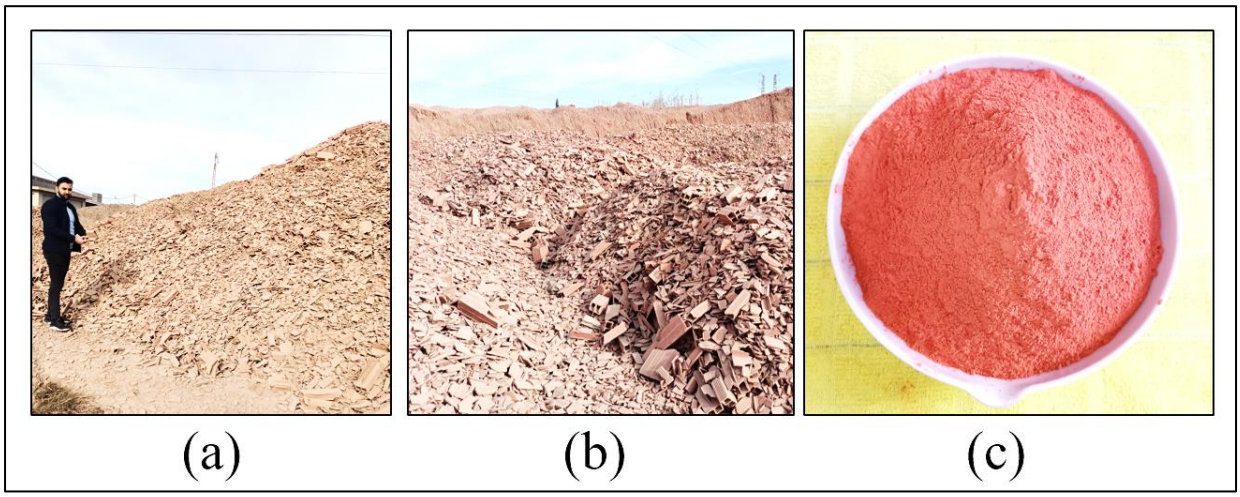

Figure 3.(a and b) Waste red bricks and (c) Powder of waste red bricks.

Table 3. The chemical and physical properties of the powder of waste red bricks [16, 17].

Chemical composition (%)		Physical characteristics	
SiO_2	70.49	Specific gravity (G_s)	2.56
Al_2O_3	13.24	Bulk density (kg/m^3)	1990
Fe_2O_3	4.72	Water absorption (%)	11.4
K_2O	3.72		
CaO	3.67		
MgO	2.13		
Na_2O	0.88		
TiO_2	0.69		
P_2O_5	0.15		
SO_3	0.10		
Cl	0.03		
Other	0.18		
LOI	0.85		

3. Experimental Program and Testing Methods

3.1. Experimental investigations

3.1.1. Specimen preparations

The preparation of mortars and cementitious composites was carried out in accordance with the specifications of the European standard EN 196-1 [18]. For the reference mortar, the following mass proportions were used: 450 ± 2 g of cement, 1350 ± 5 g of sand, and 225 ± 1 g of water, with a cement/sand ratio of 1/3 and a water/cement ratio (W/C) of 0.5.

Regarding the composites reinforced with Doum fibers, the fibers were treated with 1% NaOH for 30 minutes at room temperature, following the method developed by Achour et al [3]. A fiber content of 1.5% by weight, with a length of 10 mm, was used for all fiber-reinforced specimens, as it represents the optimal values obtained by Achour et al [7].

The mixing of fiber composites, with or without the addition of silica fume and red brick waste, was carried out following the mixing methods described by Kriker et al [19], as well as the instructions specified in the technical data sheet of the mineral admixture (silica fume).

Subsequently, the freshly prepared mixes were poured into molds for three specimens measuring 40 mm × 40 mm × 160 mm, in order to measure their physical and mechanical characteristics.

After pouring into the molds, the specimens were compacted using an impact table in accordance with the EN 196-1 standard [18]. Demoldingwas performed 24 hours after pouring. The samples were then subjected to curing in saturated water until the end of the test they were subjected to. The formulations used for the production of the samples are described in Table 4.

Table 4. The mixing ratios of mortar and composite mixes.

			In percentage (%)			In grams (g)		
Category	Mix Notation	Treated Doum Fiber (%)	Cement	SF	WRBP	C	SF	WRBP
	M0	0 %	100 %	0 %	0 %	450	0	0
	MT	1.5 %	100 %	0 %	0 %	450	0	0
	A1	1.5 %	90%	5%	5%	405	22,5	22,5
A	A2	1.5 %	85%	5%	10%	382,5	22,5	45
	A3	1.5 %	80%	5%	15%	360	22,5	67,5
	B1	1.5 %	85%	10%	5%	382,5	45	22,5
B	B2	1.5 %	80%	10%	10%	360	45	45
	B3	1.5 %	75%	10%	15%	337,5	45	67,5
	C1	1.5 %	80%	15%	5%	360	67,5	22,5
C	C2	1.5 %	75%	15%	10%	337,5	67,5	45
	C3	1.5 %	70%	15%	15%	315	67,5	67,5
	C SF WRBP	:Cement : Silica fume : waste red brick powder						

3.2. Determination of the properties of natural fiber-reinforced composites

3.2.1. Assessment of physical properties

3.2.1.1. Measurement of bulk density

The dry bulk density (ρ) in kg/m³ of hardened mortar samples at 28 and 90 days was measured according to ASTM-C140/C140M standard [20]. After each curing period, the mortar samples (40 × 40 × 160 mm³) were removed and dried in an oven at 65 °C until their mass stabilized.

Once taken out of the oven, the specimens were cooled for at least 2 hours in dry air at a temperature of 20 to 25 °C. Then, the mass of the mortars (M_d) was measured using a digital analytical balance, model AS 220.R2, from RADWAG company, with a weighing accuracy of 0.001 g.

The dimensions of the test specimens were measured using a digital caliper, and the volume (V) was calculated based on these dimensions. The mass of each sample was divided by its volume to obtain the apparent bulk density (ρ) of the material. The values of apparent density were determined for three specimens of each mortar formulation, considering the average value, and evaluated using the following expression 1:

$$\rho = \frac{M_d}{V} \qquad (1)$$

Where:

- ρ is the apparent bulk density (kg/m³),
- M_d is the mass of the mortars (kg),
- V is the volume of the specimens (m³).

3.2.1.2. Measurement of Capillary water absorption

The water absorption by capillarity corresponds to the measurement of water absorption due to capillary forces. The capillary water absorption test was carried out according to the European standard AFPC AFREM [21]. For this purpose, three specimens with dimensions of 40 × 40 × 160 mm were prepared for each mortar formulation used. After 90 days of curing, the samples were cut in half and dried in an oven at a temperature of 65 ± 2 °C until reaching a constant mass (the mass loss over 24 hours was less than 0.1%).

To allow capillary water absorption in a single direction and prevent evaporation, the four sides of the specimens were treated with a hydrophobic epoxy resin, while the opposite sides were left open. The dry mass of the specimens (M_0) was measured using a high-precision electronic balance of type ANALYTICAL BALANCE, model AS 220.R2 from RADWAG, with a weighing accuracy of 0.001 g. Then, the samples were placed in water at a constant height of 2 ± 1 mm.

The change in mass (Mt) was measured after 24 hours of water exposure. The water absorption coefficient (C) was calculated using the following equation (2):

$$C = \frac{M_t - M_0}{A} \qquad (2)$$

Where:

- C is the capillary water absorption coefficient (kg/m²),
- M_0 is the initial mass of the specimen (kg),
- M_t is the mass of the specimen at time t (kg),
- A is the submerged section of the specimen (m²).

3.2.1.3. Ultrasonic pulse velocity test

The Ultrasonic Pulse Velocity (UPV) test was used to assess the compactness, uniformity, and presence of voids or cracks in the cementitious materials. It measures the velocity of ultrasonic pulse propagation through the material. This non-destructive method allows for estimating the compressive strength and determining the modulus of elasticity of the specimens.

The measurements were conducted according to the ASTM C597-02 standard [22]. A Pundit Lab experimental device was used, applying a transmission voltage of 500 V, as shown in Figure 4. The tested specimens were samples with dimensions of 40 x 40 x 160 mm, taken after curing periods of 28 and 90 days.

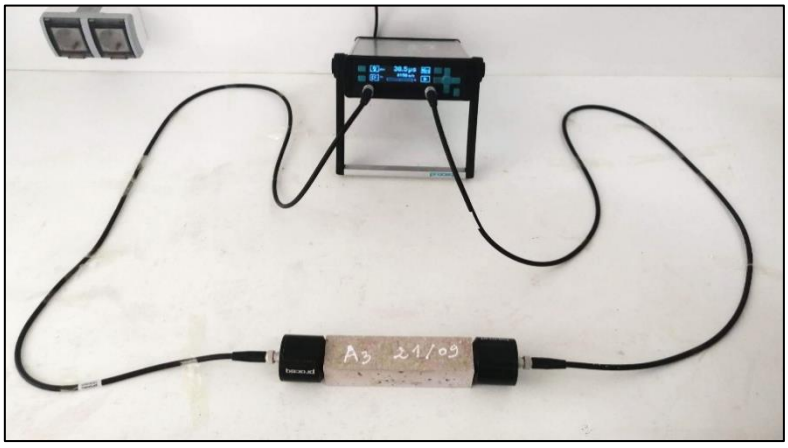

Figure 4. Ultrasonic Impulse Velocity Test.

3.2.2. Assessment of mechanical properties

3.2.2.1. Measurements of flexural tensile strength

In order to study the effect of mineral additions on the evolution of flexural tensile strength over time, three-point bending tests were conducted on prismatic specimens with dimensions of 40 x

40 x 160 mm³. These tests were performed using a UTCM-3722.FPR apparatus from UTEST, in accordance with the European standard EN 196-1 [18]. The tests were carried out after 28 and 90 days of curing, and the average of the results from three specimens was used for each mixture.

3.2.2.2. Measurements of compressive Strength

The determination of uniaxial compressive strength of cured mortars after 28 and 90 days was conducted in accordance with the standard EN 196-1 [18]. All tests were performed on a UTCM-3722.FPR testing machine from UTEST. The half-specimens used for the flexural tests were also used for the uniaxial compressive strength measurements. Six half-specimens with dimensions of 40x40x40 mm were tested for each formulation, and the average values were calculated.

4. Results and discussion

4.1. Properties of reinforced composites

4.1.1. Physical properties

4.1.1.1. The bulk density of the composites

Figure 5 illustrates the variations in bulk densities of the composites at 28 and 90 days, based on the type of substitution addition to the cement. Regarding the ternary mortars in Category A, composed of 5% silica fume and 5%, 10%, and 15% red brick waste, an increase in bulk density of approximately 14–17% is observed after a 90-day curing period compared to the fiber reference mortars. Similarly, the addition of 5% silica fume to the mixture containing 5% red brick waste leads to a maximum increase in bulk density of about 17% at 90 days, compared to the bulk density of the fiber reference mortars. Beyond 5% silica fume and 5% red brick waste, a slight decrease in bulk density is recorded.

After 90 days, Category B composites containing 10% silica fume and varying proportions of red brick waste (5%, 10%, and 15%) exhibit a bulk density increase of 20–28% compared to the fiber reference mortar. Consequently, the highest bulk density of the ternary composites is achieved with an optimal content of 10% silica fume and 5% red brick waste by weight of cement, representing a 28% increase over the fiber reference mortar.

For Category C mixes, based on 15% silica fume and different percentages of red brick waste (5%, 10%, and 15%) by weight of cement, the bulk density increase at 90 days ranges from 14.5–19% compared to the fiber reference mortar. The highest increase for these mixes is

obtained with 15% silica fume and 5% red brick waste content, representing a bulk density increase of over 19% compared to the fiber reference mortar.

The results show that fiber composites with 10% silica fume and 5% red brick waste exhibit the highest bulk density among all the mixes in the three categories of composites produced.

This growth is logically explained by:

- The fact that the cement-replacing additives have a finer particle size than cement itself. Silica fume consists of ultrafine spherical particles, nearly 100 times smaller than cement grains, while red brick waste powder has a higher specific surface area compared to cement. This fills the pores of the cementitious materials, leading to a reduction in porosity, particularly in the porous transition zone (ITZ) between the cement paste and the aggregate and fiber, thereby providing a dense microstructure and increasing the bulk density of the composite [23–26].

- Due to their extreme fineness and high silica content, silica fume and red brick powder are highly effective pozzolanic materials. In the presence of water and calcium hydroxide, they react with water and form hydrated calcium silicate (C-S-H) gels, which fill a portion of the pores, thereby reducing porosity and densifying the microstructure [26, 27].

Furthermore, the bulk density of the composites continues to increase with curing time. It should also be noted that the bulk density slightly decreases with an increase in the substitution percentage for all composites. This decrease is mainly due to a more significant increase in ultrafine particles, resulting in an excess of the small-sized fraction of low density. This starts to displace the sand and Portland cement grains, leading to a decrease in the bulk density of the cured composites [25], [28], and [29]. These results are consistent with previous research [15], [28], and [30].

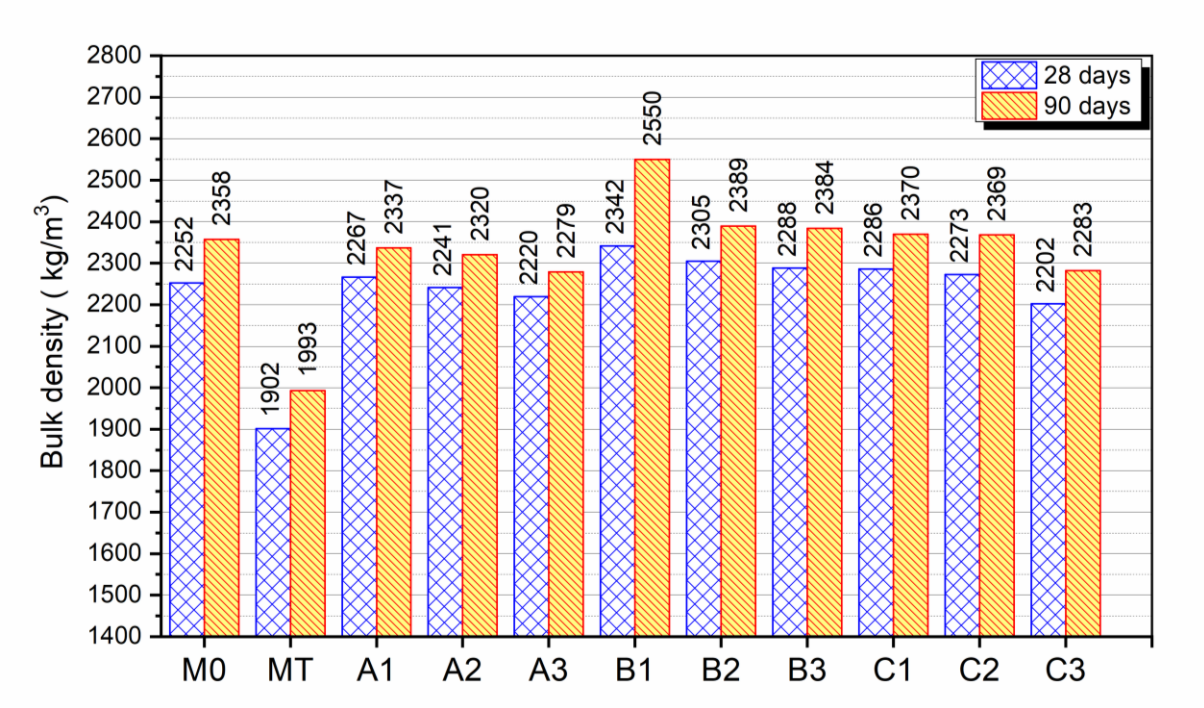

Figure 5. Bulk density of the studied mixtures as a function of SF and WRBP content.

4.1.1.2. Capillary water absorption of composites

The results of the capillary absorption tests conducted after 24 hours in water on Doum fiber-reinforced samples, as a function of the cement substitution rate by the two mineral additives after 90 days of water curing, are presented in Figure 6. It can be observed that the incorporation of silica fume and red brick waste as partial replacements for Portland cement in Doum fiber-reinforced mortars leads to a decrease in the absorption of the composites, with an increase in the substitution rate.

However, after 90 days of curing, the partial replacement of cement with 10% silica fume and various percentages of red brick waste (5%, 10%, and 15%) resulted in a reduction in absorption for category A composites. This reduction ranged from 11.5% to 26% compared to the reference fiber mortar. The increase in additional amounts of silica fume and red brick waste led to a slight increase in absorption, although it remained lower than that of the reference fiber mortar.

On the other hand, compared to fiber mortars containing only Portland cement without additives, the ternary binder-based mortars (cement + 10% silica fume and 5%, 10%, and 15% red brick waste) exhibited a low water absorption capacity compared to other categories of composites. After a 90-day period, a decrease in absorption ranging from 43% to 47.5% was observed compared to the reference fiber mortar. Mix B1 recorded the lowest absorption

coefficient, with a reduction of approximately 47.5% at 90 days compared to the reference fiber mortar.

Similarly, for category C composites, a decrease in absorption at 90 days was observed, ranging from 21.5% to 39% compared to the reference fiber mortar. However, it is important to note that the capillary absorption of fiber composites increased with the increase in the substitution rate.

These results can be primarily attributed to:

- The mineral additives used in this study consist of extremely fine particles, which improve the compactness of hardened mixes and reduce porosity. Silica fume, composed of ultrafine spherical particles, and red brick waste powder, with their high specific surface area, fill the pores of cementitious materials. This results in a reduction in porosity, particularly in the porous transition zone between cement paste, aggregate, and fibers, leading to a more compact microstructure and a reduction in capillary absorption of the obtained composites [24–27].

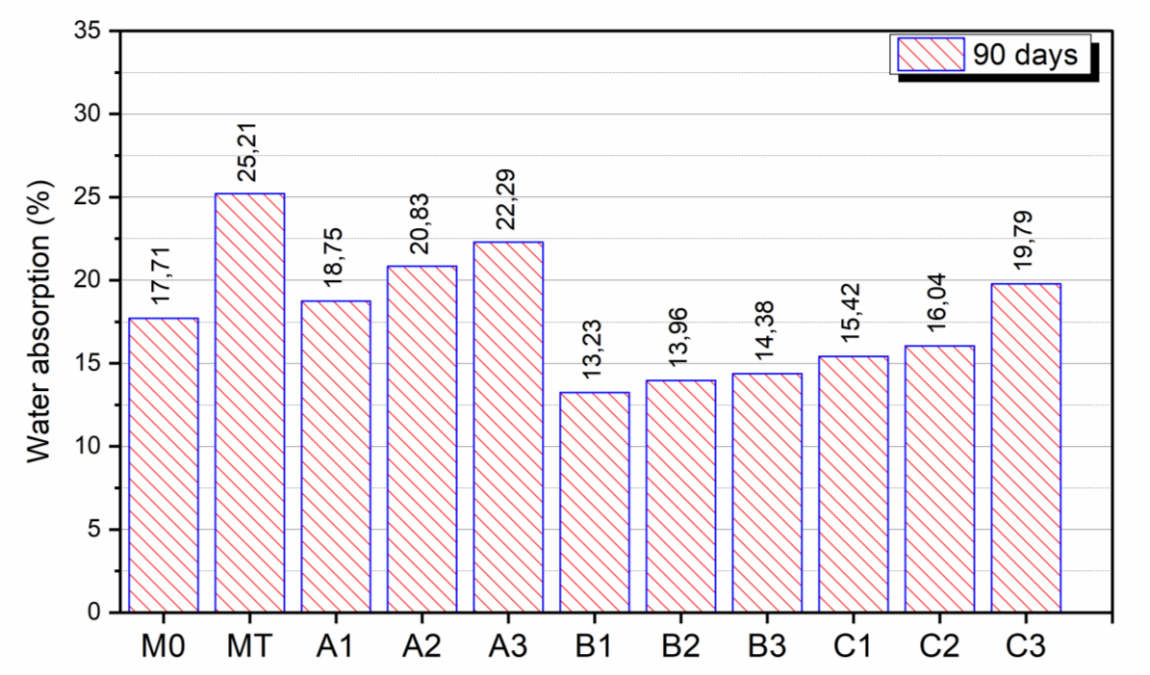

Figure 6. Water absorption of the studied mixtures as a function of SF and WRBP content after 24 hours.

4.1.1.3. Ultrasonic wave propagation velocity

The values of ultrasonic pulse velocity (UPV) for different mortars are presented in Figure 7. The results indicate that the partial replacement of cement with silica fume and red brick waste

powder increased the UPV values. The UPV value for the reference fiber mortar at 90 days was 3424 m/s, which is considered average quality [31–32]. For category A mortars, with a partial cement replacement rate of 5% silica fume and 5%, 10%, and 15% red brick waste, UPV values ranging from 4011 to 4088 m/s were obtained, classifying these mortars as good quality. Furthermore, category B composites, for mixes B1, B2, and B3, recorded UPV values ranging from 4386 to 4709 m/s at 90 days. The highest UPV value of 4709 m/s was recorded for composite B1, classifying it as excellent quality. Indeed, the 90-day UPV values of category C composites, for mixes C1, C2, and C3, recorded values ranging from 3977 to 4305 m/s, which is considered good quality for mortar [31–32]. These results are related to the use of mineral additives, such as silica fume and red brick waste powder, which replace cement in this study. Due to their fineness, they are capable of filling the pores of cementitious materials, reducing porosity and creating a dense microstructure. The reaction of these silica-rich materials with water leads to the formation of hydrated calcium silicate gels, further strengthening the density and reducing porosity. This improvement in compactness and density contributes to enhancing the quality of the produced composites [25–31].

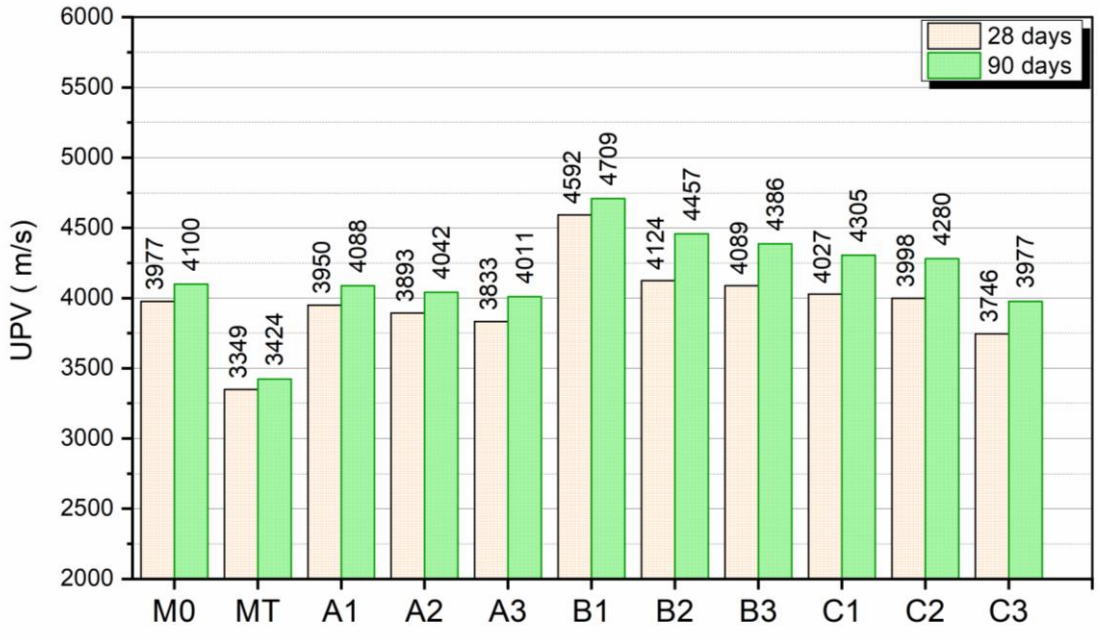

Figure 7. Ultrasonic Pulse Velocityof the studied mixtures as a function of SF and WRBP content.

4.1.2. Mechanical properties

4.1.2.1. Effect of mineral additions on compressive strength

The compressive strength values of different mixes containing varying percentages of additives, as illustrated in Figure 8, generally show a significant improvement in the compressive strength of mixes with a higher substitution rate.

The incorporation of 5% silica fume and 5%, 10%, and 15% red brick waste as substitutes for cement in category A mortars increased their compressive strength at 90 days by 30–51% compared to the reference mortar. An optimum is observed for a substitution rate of 5% silica fume and 5% red brick waste, with a 51% increase in strength compared to the reference fiber mortars.

On the other hand, for category B fiber mortars with 10% silica fume and different percentages of red brick waste powder (5%, 10%, and 15%), the increase in compressive strength is approximately 66-109% after a 90 day curing period compared to the reference fiber mortar. During the same curing period, the results indicate a maximum improvement in compressive strength of approximately 109% for composites containing 10% silica fume and 5% red brick waste by weight of cement, beyond which the strength decreases.

Regarding category C composites, made with 15% silica fume and varying proportions of red brick waste (5%, 10%, and 15%) by weight of cement, the compressive strength at 90 days increased by 26–65% compared to the reference composite. These results highlight the existence of an optimal dosage of mineral additives where the compressive strength is maximum. This optimum was recorded with the introduction of 15% silica fume and 5% red brick waste as partial cement replacement.

The examination of the results shows that for all formulations of the three categories of mixes, the best performance is achieved with the addition of 10% silica fume and 5% red brick waste as partial cement replacement, resulting in the highest strengths at 90 days.

The increase in compressive strengths is related to two main factors:

- The pozzolanic reaction between silica and lime in the presence of water. The additives used are of a pozzolanic nature and contain 80–95% silica (SiO_2). They react with the calcium hydroxide (or portlandite) resulting from the hydration of clinker, forming strength-generating hydrates such as C-S-H, calcium aluminate, and calcium silicoaluminate [15], [26], [33], and [34].

- The mineral additives that partially substitute the cement matrix in this study are composed of extremely fine particles, which increase the compactness of hardened mixes and reduce porosity, resulting in improved strengths [15], [26], [34], and [35].

Furthermore, the compressive strength values of mortars made by partially replacing cement with these mineral additives increase over time at different ages, regardless of the nature and rate of the additive.

On the other hand, it is observed that the higher the substitution rate of mineral additives in the studied mortars, the lower the compressive strength of the produced composites. This is because the increase in the use of mineral additives reduces the amount of cement in mortar mixes, significantly affecting the development of strength in cementitious composites based on the hydration process. Therefore, the compressive strength produced by the pozzolanic reaction of large amounts of mineral additives in mortars cannot compensate for the compressive strength developed by the hydration reaction of cement [36, 37].

The obtained results are in agreement with observations reported in the literature [26, 27, 38–40].

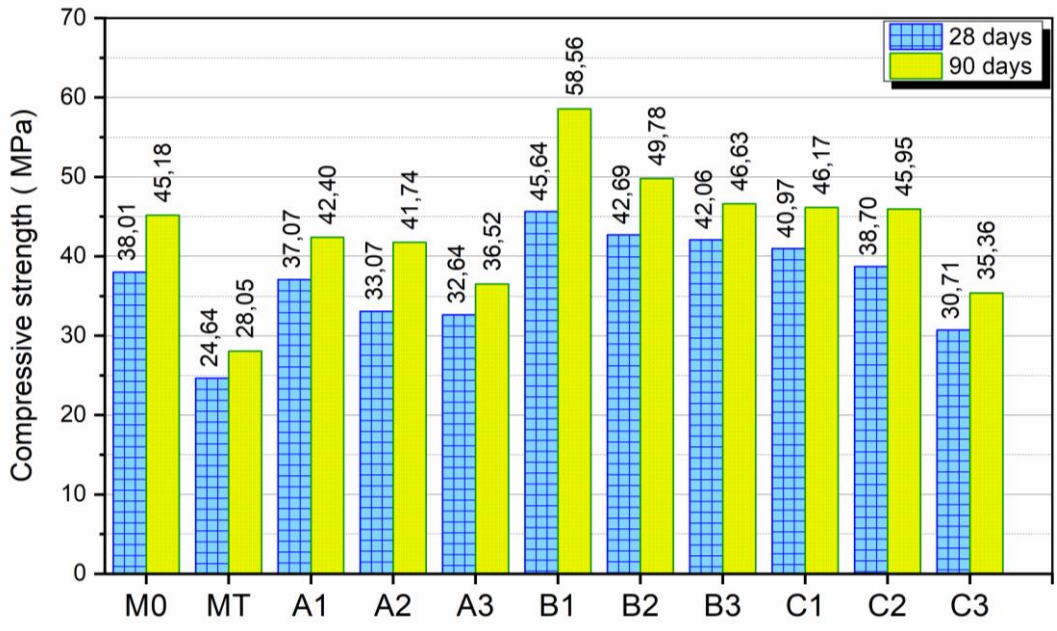

Figure 8. Compressive strengthof the studied mixtures as a function of SF and WRBP content.

4.1.2.2. Effect of mineral additions on the flexural strength

The results of flexural strength tests conducted on Doum fiber-reinforced samples as a function of the amount of cement substitution by the two mineral additives after 28 and 90 days of water curing are presented in Figure 9. It can be observed that the use of silica fume and red brick waste powders as partial replacements for Portland cement in Doum fiber-reinforced mortars led to an increase in the flexural strengths of the composites, with an increase in the substitution rate and curing age.

However, at 90 days of age, the partial replacement of cement in category A mortars with 10% silica fume and various rates of red brick waste (5%, 10%, and 15%) resulted in an improvement in flexural strength ranging from 17–21% compared to that of the reference fiber mortar. Additional additions of silica fume and red brick waste decreased the flexural strength, but it still remained higher than that of the reference fiber mortar.

In contrast, compared to fiber mortars made solely with Portland cement and without additives, mortars made with ternary binders (cement + 10% silica fume and 5%, 10%, and 15% red brick waste) showed better flexural strength results, with an increase ranging from 22–26% at 90 days. Furthermore, the highest flexural strength was found for mix B1, where a clear increase in flexural strength at 90 days of approximately 26% compared to that of the reference fiber mortar can be observed. The optimum was observed at 10% silica fume and 5% red brick waste for flexural strength.

Indeed, the flexural strength at 90 days of category C composites for mixes C1, C2, and C3 increased by 21%, 20.6%, and 18% respectively compared to the reference fiber mortar. Similarly, the flexural strength of fiber composites increased with increasing substitution rates, but beyond certain critical values, it decreased.

These results are primarily due to :

- The effect of partial cement substitution by the two mineral additives, causing a decrease in the alkalinity and $Ca(OH)_2$ content of the cementitious matrix, which is responsible for the degradation, mineralization, and embrittlement of the fibers. It is interesting to note that the aggressiveness of the cementitious matrix towards plant reinforcements is partly linked to the highly alkaline pH of the interstitial environment and the presence of calcium hydroxide, which diffuses towards the fibers and precipitates, causing their mineralization and resulting in a decrease in mechanical performance and durability of the composites reinforced with these fibers. Moreover, the presence of lime in the interstitial solution causes the dissolution of the amorphous components of the plant fiber when used as reinforcement. Thus, the use of pozzolanic mineral additives is highly effective in consuming $Ca(OH)_2$ through the pozzolanic reaction, thereby eliminating the mineralization and degradation of fibers while maintaining the ductility and durability of the composite over time [4], [7], and [41].

- The increased compactness of the mixes due to the filling effect caused by the ultrafine particles of the mineral additives used, leading to composites with a highly dense microstructure and very fine porosity, as well as filling the tiny voids in the transition zone, thus optimizing interfacial adhesion strength and compatibility between the fiber and the matrix [7], [42], and [43].

- The pozzolanic nature of the mineral additives used, which, in the presence of water and lime, allow the formation of hydrated calcium silicates (C-S-H), the main product responsible for strength, thereby improving the mechanical performance of cementitious composites [44–47].

These results are in accordance with previous research [42–47].

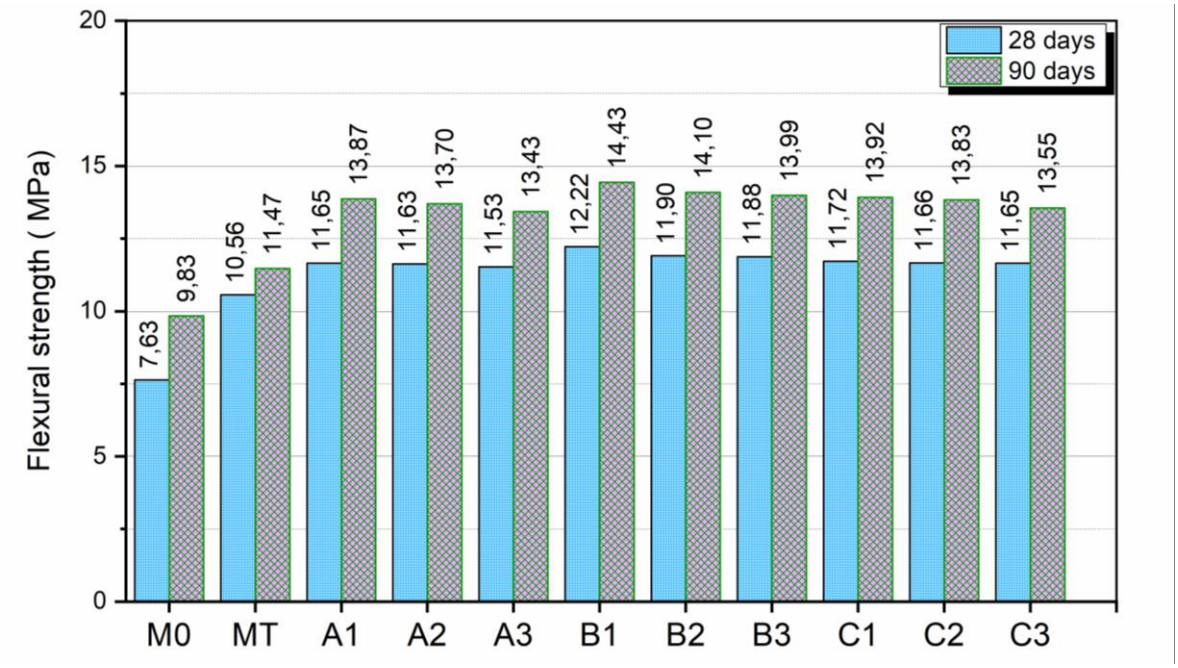

Figure 9. Flexural strengthof the studied mixtures as a function of SF and WRBP content.

5. Conclusions

The results obtained in this study show that the incorporation of silica fume and red brick waste as partial substitutes for cement in Doum fiber-reinforced mortar-based composites leads to significant improvements in material properties.

Regarding bulk density, a progressive increase is observed with curing time for all the studied mixtures. Ternary composites containing 10% silica fume and 5% red brick waste exhibit the highest bulk density among all the formulations.

Similarly, the absorption of the composites decreases with an increase in the substitution rate of cement by mineral additives. Mixtures with 10% silica fume and 5% red brick waste record the lowest water absorption capacity compared to other formulations.

Furthermore, the ultrasonic pulse velocity (UPV) is improved with the addition of silica fume and red brick waste powder. The composites show higher UPV values, indicating better quality and a denser microstructure.

Indeed, in terms of compressive strength, a significant improvement is observed with the addition of additives. Composites containing 10% silica fume and 5% red brick waste recorded the highest strength values at 90 days, with increases of up to 109% compared to the reference fiber mortar. However, beyond certain additive concentrations, the compressive strength decreased.

Regarding flexural strength tests, an increase in strength is observed with the addition of additives, reaching improvements of up to 26% compared to the reference fiber mortar for composites containing 10% silica fume and 5% red brick waste.

In conclusion, composites containing 10% silica fume and 5% red brick waste exhibited the best performance in all the studied properties. However, it is important to note that increasing the usage rate of additives beyond certain concentrations may lead to a decrease in the properties of the composites.

The use of silica fume and red brick waste as cement substitutes in Doum fiber-reinforced cement-based composites holds potential for improving material performance. These results can contribute to the development of sustainable and environmentally friendly construction materials by utilizing alternative resources and reducing the environmental impact of the cement industry. However, further studies are needed to deepen the understanding of the mechanisms and properties of the composites obtained from these additives.

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